Generic scheduling framework and algorithm for time-varying wireless networks

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Generic Scheduling Framework and Algorithm for Time-Varying Wireless Networks

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***Abstract*— In this paper, the problem of scheduling multiple users sharing a time varying wireless channel is studied, in networks such as in 3G CDMA and IEEE 802.16. We propose a new generic Wireless Packet Scheduling Framework (WPSF), which takes into account not only the quality of service (QoS) requirements but also the wireless resource consumed. The framework is generic in the sense that it can be used with different resource constraints and QoS requirements depending on the traffic flow types. Subsequently, based on this framework a Minimum Rate and Channel Aware (MRCA) scheduling algorithm is presented. MRCA attempts to greedily enhance wireless channel efficiency by making use of multi-user channel quality diversity, while providing acceptable QoS in term of users' minimum rate constraints. Simulation results show the desirable properties identified in the algorithm.**

I. Introduction

Wireless communications systems have developed rapidly in the past few years. Packet scheduling is becoming a very challenging task for wireless networks due to the scarcity of radio resources, error-prone channel conditions and diversity of flow types and their Quality of Service (QoS) requirements. Because wireless resource is scarce and expensive, good packet scheduling schemes in wireless networks should be able to improve wireless resources efficiency in terms of bandwidth, transmission power, etc. In addition, wireless packet scheduling policies should guarantee users' QoS requirements in terms of average service rate, average delay, minimum delay, and packet loss rate according to flow types of users.

Time-varying characteristics of wireless channels origi-nates from the application of adaptive resource allocation techniques, such as adaptive modulation and coding schemes and adaptive power allocation. Adaptive Modulation and Coding (AMC) schemes have been widely used to match transmission parameters in the physical layer [1]. AMC deals with the error-prone channel conditions of wireless links and reduces the Bit Error Rate (BER) in the physical layer and Packet Error Rate (PER) in the Media Access Control (MAC) layer. When transmission conditions deteriorate, AMC may choose, for example, a more robust FEC scheme and lower modulation mode to increase the probability of successfully transmitting packets. AMC reverts to a simple FEC scheme and higher modulation mode when channel conditions improve. Adaptive power allocation is applied to dynamically adjust the transmission power based on the channel quality [2][3]. High SNR can be achieved in the expense of transmission power. These new technologies also make it necessary to combine packet scheduling with the AMC mechanism and power allocation in the physical layer, so as to use the wireless resources more efficiently. A scheduling framework and schemes for wireless networks were presented in [4][5]. In particular, these papers assume that wireless channel has only two states, i.e., good or bad, which is different from ours. We deal with the scenario where wireless channel has multiple states. Wireless scheduling schemes were also considered in [6]$\sim$[10]. These schemes try to restrict the average allocations and improve the overall system resource utility by exploiting the diversity characteristic in wireless channel.

In this paper, we propose a new generic Wireless Packet Scheduling Framework (WPSF) for packet scheduling in time-varying wireless networks. WPSF takes into account not only the quality of service requirements but also wireless resource constraints of users. WPSF consists of three parts: Resource Indicator, Service Monitor and Profit Calculator. Following the above framework, a Minimum Rate and Channel Aware (MRCA) scheduling algorithm is presented in the paper. This algorithm uses the above framework, where channel efficiency and minimum service rate are unique wireless resource constraint and user's QoS requirement accordingly. Simulation results show that MRCA can improve channel efficiency, while meeting users' minimum service rate requirements.

The remainder of this paper is organized as follows. In Section II, the system model is presented and in Section III, a new generic wireless packet scheduling framework for packet scheduling in time-varying wireless networks is proposed. In this section we also analyze some implementation-dependent questions in relation to this framework. A MRCA scheduling algorithm based on the framework is presented in Section IV. Section V contains numerical results for the performance of the scheduling algorithm and Section VI contains our conclusions.

II. System Model

We investigate a cell TDMA system consisting of a base station (BS) and N users. The wireless channel between BS and users is shared by N users under the control of the packet scheduler residing in BS both in uplink and downlink. The physical layer works in TDMA mode, where time is divided into time slots. The time slot duration is fixed and BS can serve only one user during each time slot. The scheduler in BS allocates time slots to N users based on their QoS requirements and wireless resource constraints. The exact bits that can be sent in each time slot depend on the modulation and coding schemes applied which is time varying and user dependent. Each user maintains its own queue in BS, where packets wait for service. Within each queue, packets are served in a FIFO (first in first out) order. For simplicity, we will choose channel efficiency as a unique wireless resource in our case study. However, our analysis is applicable to other wireless resource considerations.

We use $AR_i(t)$ in bits per second to denote the available transmission rate of user i at time t. $AR_i(t)$ is a parameter that tracks the channel quality and it is determined by the modulation and coding schemes and Bit Error Rate (BER) in physical layer. AMC dynamically chooses modulation and coding schemes according to channel qualities. BER is also an indication of channel qualities. High $AR_i(t)$ means good channel quality and vice versa. $AR_i(t)$ belongs to [AR_i^{min}, AR_i^{max}] , where $AR_i^{min}(t)$ is the minimum available transmission rate and $AR_i^{max}(t)$ is the maximum one.

Let T_{slot} denote the length of each time slot. The number of bits that can be transmitted in current time slot for user i can be calculated as follows:

$$Number\ of\ bits = AR_i(t)T_{slot}. \tag{1}$$

which means high $AR_i(t)$ can serve more bits using the same time duration. Likewise, low $AR_i(t)$ may need more time to transmit the same amount of bits in packet.

We can use $CE_i(t)$ to stand for the normalized channel efficiency for user i at time t, and it is expressed as:

$$CE_i(t) = \frac{AR_i(t)}{AR_i^{max}}. \tag{2}$$

where AR_i^{max} is the maximum available transmission rate as defined above and $AR_i(t)$ is the current available transmission rate for user i at time t.

Let $ACE(t)$ denote the system average channel efficiency by time t and we have:

$$ACE(t) = \frac{\int_0^t CE_{S(t)}dt}{t}. \tag{3}$$

where

$$S(t) = i;\ i = (1, 2, ..., N). \tag{4}$$

$S(t)$ is the scheduling policy. Policy $S(t)$ determines which user to serve in current time slot. If S(t) equals to i, then the current time slot is allocated to user i and the system receives a reward of $CE_i(t)$ in channel efficiency. Let $RS_i(t)$ in bits per second denote the service rate received by user i by time t. $RS_i(t)$ can be defined ideally as follows:

$$RS_i(t) = \frac{\int_0^t AR_i(t)L_{\{s(t)=i\}}dt}{t}. \tag{5}$$

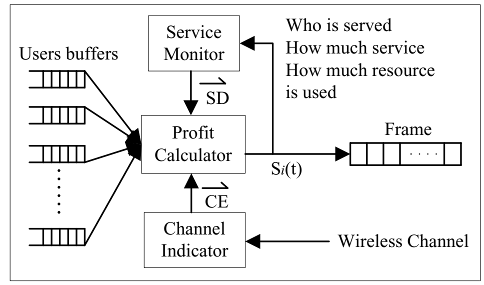

Fig. 1: Wireless Packet Scheduling Framework

where

$$L_A = \begin{cases} 1;\ if A\ occurs \\ 0;\ otherwise \end{cases} \tag{6}$$

We use RM_i in bits per second to indicate the minimum service rate requirement of user i. When user's average service range is large than RM_i , users can perceive a good service quality; otherwise, service quality deteriorates rapidly. Our goal is to design a scheduler, $S(t)$, which maximizes the system average channel efficiency, while satisfying the minimum rate constraints of users. The problem can be stated formally as follows:

$$\begin{aligned} &maximize\ \ ACE(t, S(t)) \\ &s.t.\ RS_i(t, S(t)) \geq RM_i \end{aligned} \tag{7}$$

In the following sections, we first present our framework for wireless packet scheduling and then we describe a practical algorithm based on our framework.

III. Framework For Wireless Packet Scheduling

Based on the analysis above, the goal of our Wireless Packet Scheduling Framework (WPSF) is to maximize the system average channel efficiency by exploiting the time-varying and user-dependent wireless channels. Generally, the scheduler tries to allocate time slots to users with relatively better channel quality, while taking into account QoS requirements of users.

WPSF consists of three parts: Channel Indicator, Service Monitor and Profit Calculator, as depicted in Fig 1. The Channel Indicator module traces the current wireless channel qualities of users and chooses the proper transmission schemes and transmission power for users The Service Monitor module measures how users have been served in the past based on the services received and QoS requirements of users. The Profit Calculator module calculates the profit of the system if user i were served in the current time slot and then chooses the user with the highest profit to serve. Next, we explain each module of the framework in detail and discuss some design considerations.

Channel Indicator indicates the channel efficiency if user i is chosen to transmit in the current time slot. Let $\overrightarrow{CE(t)}$ = (CE_1(t),CE_2(t),...,CE_N(t)) denote the output of Channel Indicator. We have:

$$CE_i(t) = \frac{AR_i(t)}{AR_i^{max}}. \tag{8}$$

Channel Indicator updates $\overrightarrow{CE(t)}$ based on resource usage information, i.e., the modulation and coding schemes and BER in the physical layer. As we mentioned above, the diversity of channel qualities comes from the fact that channels between users and BS are time-varying and user-independent. In the uplink case, where packets are sent from users to BS, Channel Indicator can get resource usage information from the physical layer directly. While in the downlink case, users get this information and send it back to BS in a predefined channel. This results in the scheduler in BS having the full knowledge of resource usage information. $\overrightarrow{CE(t)}$ is used by the scheduler to differentiate between users with different channel qualities. $CE_i(t)$ becomes high if the channel between user i and BS is of good quality, otherwise, $CE_i(t)$ becomes low. In order to improve the system channel efficiency as much as possible, the scheduler may attempt to serve the user with the largest $CE_i(t)$. For example, if there are two users at time t with $CE_1(t)$ = 0.3, $CE_2(t)$ = 0.7, then user 2 would be served if channel efficiency was the only consideration.

The Service Monitor module determines how users have been served based on the QoS requirements and the actual services received in the past. Service Monitor consists of two subparts: Reference Service and Received Service. Reference Service submodule generates a reference for the amount of service that should have been received by a user in order to guarantee the prescribed service QoS. Reference service is produced based on users' QoS requirements. Typically, we use minimum service rate, average service rate and average delay to denote users' QoS requirements based on the type of flows. For example, if user i's minimum service rate is equal to RM_i, then during time interval [t1, t2], the amount of service equivalent to at least RM_i(t2-t1) bits should be received by user i in order to maintain the prescribed QoS. Received Service submodule updates the service statistics, which are used to indicate how users have been served in the past. Let $\overrightarrow{RS(t)}$ = (RS_1(t),RS_2(t),...,RS_N(t)) denote the Received Service by time t and $\overrightarrow{RF(t)}$ = (RF_1(t),RF_2(t),...,RF_N(t)) denote the Reference Service that should be allocated to users. We use $\overrightarrow{SD(t)}$ = (SD_1(t),SD_2(t),...,SD_N(t)) to denote the measure of "need" for users to be served at time t. Higher $SD_i(t)$ denotes that user i has greater need to be served. We call $SD_i(t)$ the "Service Degree" parameter and we define it as follows:

$$SD_i(t) = F(RS_i(t), RF_i(t)). \tag{9}$$

The Profit Calculator model calculates the system profit $P_i(t)$ if user i is served in the current time slot. We define $P_i(t)$ as:

$$P_i(t) = G(SD_i(t), CE_i(t)). \tag{10}$$

to calculate the profit of serving user i at time t based on the Service Degree parameter $SD_i(t)$ and Channel Quality parameter $CE_i(t)$. The Profit Calculator then chooses the user with the largest $P_i(t)$ to serve, i.e.,

$$SD(t) = \underset{i}{arg}\ max P_i(t). \tag{11}$$

There are several open considerations that are of great importance to the scheduling algorithm design and actual implementation of WPSF. Next we list them and provide some possible solutions. In Section IV, we will provide our MRCA scheduling algorithm by systematically solving these considerations.

CS 1: How to statistically trace the real services allocated to users by updating $RS_i(t)$? This should be done based on the history of service allocation. A simple way may be to apply a sliding window to calculate the average service received. The sliding window slides as time goes by and the evaluated average service rate is updated. In this case, the sliding window's size is a key factor that decides the scheduler performance. There are some other mechanisms applied in [12].

CS 2: How to calculate Reference Services $RF_i(t)$? This depends on the type of flow and QoS parameters used. For example, many data services have a constraint on minimum service rate, which decides the least services to be received within a time interval. So we can periodically produce idealized service requirements in the minimum service rate as a reference.

CS 3: How to calculate the service degree parameter SDi(t) as a function F($RS_i(t)$,$RF_i(t)$) indicating how users have been served based on $RS_i(t)$ and $RF_i(t)$. Generally speaking, high $SD_i(t)$ indicates that user i has been served well and vice versa.

CS 4: What kind of G($SD_i(t)$,$CE_i(t)$) to use to do the tradeoff between QoS parameter $SD_i(t)$ and channel efficiency parameter $CE_i(t)$, so that system channel efficiency can be greatly improved while QoS requirements can be met.

The scheduler can perform the scheduling at each time slot as follows:

Step 1: Initialize $\overrightarrow{RS(t)}$, $\overrightarrow{RF(t)}$ and $\overrightarrow{CE(t)}$.
Step 2: Calculate $\overrightarrow{SD(t)}$ by F($\overrightarrow{RS(t)}$,$\overrightarrow{RF(t)}$).
Step 3: Calculate $\overrightarrow{P(t)}$ using G($\overrightarrow{SD(t)}$,$\overrightarrow{CE(t)}$).
Step 4: Choose the user i with best $P_i(t)$ to serve.
Step 5: Update $\overrightarrow{RS(t+1)}$ based on the scheduling result
Step 6: Goto Step 2 for the next time slot

Based on the WPSF framework, we can readily create a new efficient scheduling algorithm that will reflect considerations CS1-CS4 listed above. In the next section we present such a new scheduling algorithm which we call MRCA (Minimum Rate and Channel Aware).

IV. MRCA Scheduling Algorithm

We will present the MRCA scheduling algorithm by answering the open considerations of the wireless scheduling framework presented in Section III.

The first consideration is to create a mechanism to trace the Received Service in the past. This history information indicates how the user has been served and will be used by the scheduler to perform any compensation, if required. This means that poorly served users are more likely to be served than well served users.In MRCA, we use a sliding window to maintain the history of packet scheduling and update it according to the scheduling result as time goes by. Let M denote the number of time slots in the sliding window length, and let $V_i(k)$ denote the k'th bandwidth allocated to user i. We define $V_i(k)$ as follows:

$$V_i(k) = \begin{cases} Bandwidth(bps), & \text{if user } i \text{ is served,} \\ 0, & \text{otherwise.} \end{cases} \tag{12}$$

then $RS_i(t)$ can be calculated by :

$$RS_i(t) = \frac{\sum_{k=1}^{M} V_i(k)}{M}. \tag{13}$$

Sliding Window is updated as follows: the eldest allocation item $V_i(M)$ is removed from the tail of the Sliding Window, and a new allocation item is added to the head, whenever one scheduling process is finished.

The second consideration is how to calculate the Reference Service according to QoS requirements of users. As described in Section II, since the minimum service rate is the only QoS requirement considered in this paper, we can simply calculate the Reference Service as follows:

$$RF_i(t) = RM_i. \tag{14}$$

The third consideration is how to calculate the Service Degree parameter $RS_i(t)$ for user i based on $RF_i(t)$ and $RS_i(t)$. In this paper, we propose the following expression to calculate this parameter:

$$SD_i(t) = \frac{RS_i(t) - RF_i(t)}{RF_i(t)}. \tag{15}$$

Higher $SD_i(t)$ indicates that user i has received better service and vice versa. $SD_i(t)$ belongs to $[-1,\infty)$. When $SD_i(t) < 0$, it indicates user i received less service than the minimum service rate constraint and user's QoS will deteriorate greatly. In this case, the scheduler should give extremely high priority to serve these users. Taking this concern in mind, we solve the final consideration of calculating the profit of serving user i as follows.

$$P_i(t) = \begin{cases} P_{max} - SD_i(t), & \text{if } \mathrm{SD}_i(\mathrm{t})<0, \\ CE_i(t), & \text{otherwise.} \end{cases} \tag{16}$$

where, P_{max} is a fixed parameter and we have

$$P_{max} > max(CE_i(t)). \tag{17}$$

From the above we can seen that users are divided into two categories: users with $SD_i(t)$ less than 0 and users with $SD_i(t)$ not less than 0. The first category users have higher service priority than those in the second category. Among the first category, we further aim to give priority to users who have received the worst service by time t in order to improve their QoS. On the other hand, in the second category all users are already receiving their minimum QoS requirement we aim to give priority to users with the best channel quality in order to maximize system channel efficiency. As a result, optimal scheduling selection, S(t), can be defined as follows:

$$S(t) = \underset{i}{arg}\ maxP_i(t). \tag{18}$$

Based on the discussion above, our MRCA wireless scheduling algorithm can be described as follows.

Step 1. Initialize all users' sliding windows by $V_i(k) = 0$ for $k = 1, 2, ,M$. Calculate $\overrightarrow{RF(t)}$ by $RF_i(t)=RM_i$.

Step 2. Calculate $\overrightarrow{RS(t)}$ as: $RS_i(t) = \frac{\sum_{k=1}^{M} V_i(k)}{M}$, for all users

Step 3.Calculate $\overrightarrow{SD(t)}$ by: $SD_i(t) = \frac{RS_i(t)-RF_i(t)}{RF_i(t)}$, for all users

Step 4. Get $\overrightarrow{CE(t)}$ and calculate user's profit by :

$P_i(t) = \begin{cases} P_{max} - SD_i(t), & \text{if } \mathrm{SD}_i(\mathrm{t})<0, \\ CE_i(t), & \text{otherwise.} \end{cases}$, for all users

Step 5. Serve user $i = \underset{i}{arg}\ maxP_i(t)$.

Step 6. Update sliding window and go to Step 2, repeat the steps for the next scheduling time slot.

V. Simulation Results

In this section we present the simulation results to evaluate performance of the MRCA packet scheduling algorithm. For simplicity, we only consider a TDMA cell system with only one base station. In the simulation scenario we increase the number of users in the system and observe the resulting average channel efficiency and delay. The time-varying channel is represented by a multi-state Markov Chain [14][15]. We simulate the difference in channel qualities by changing the state transmission probabilities in the Markov chain. All users in our simulation scenario have identical QoS requirements.

A. Channel Efficiency Improvement

Fig 2 shows the average channel efficiency improvement when the number of users increases and system capacity becomes over loaded. We compare the channel efficiency improvement of MRCA with that of the Best Channel First (BCF) and Longest Queue First (LQF) scheduling algorithms. BCF chooses the user with the best channel quality to serve at each time slot, so it can achieve high channel efficiency when the number of users increases as shown in Fig 2. Because BCF pays no attention to the QoS requirements of users, it can't guarantee the minimum service rates of users leading to a high average delay especially when system capacity becomes high. This is shown in Fig 3 where average delay of users is depicted with the increase of the number of users. On the contrary, LQF tries to allocate bandwidth fairly to users but it takes no account of the channel qualities in the wireless link. LQF can guarantee a low average delay as shown in Fig 2. However, this produces low channel efficiency as shown in Fig 3. Compared with BCF and LQF, our MRCA algorithm tries to improve channel efficiency by choosing the best channel quality user to serve when system capacity is underloaded. MRCA also aims to guarantee users' minimum service rate requirements when users are poor served. As a result, MRCA can improve channel efficiency rapidly when the number of users increases while at the same time it has a relatively low average delay compared to BCF. When the user number is more than 16 in our simulation scenario, MRCA tries to guarantee the minimum service rate constraints at the expense of channel efficiency. This results in average channel

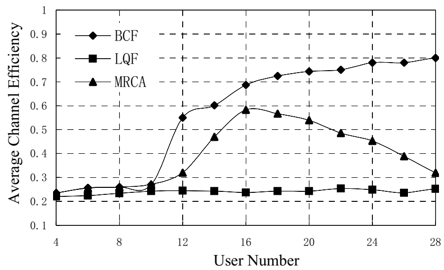

Fig. 2: Average Channel Efficiency vs User Number

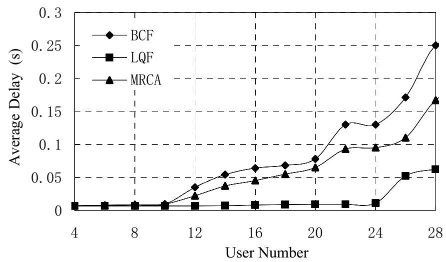

Fig. 3: Average Delay vs User Number

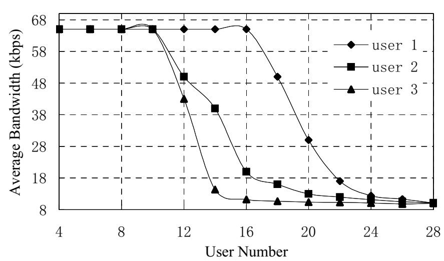

Fig. 4: Average Bandwidth vs User Number

efficiency decreasing and average delay increasing as shown in Fig 2 and Fig 3. However, as shown in the section below minimum service rate requirements of users are met.

Generally, MRCA produces high channel efficiency when the system capacity is not overloaded and it attempts to guarantee the minimum rate requirements when the system be-comes overloaded.

B. *Minimum Rate Guarantee*

Fig 4 shows how MRCA guarantees minimum rates re-quirements of users, when the system capacity becomes over loaded. We assign user 1, user 2 and user 3 to different channel qualities and to the same minimum rate guarantee requirements of 10kbps. Let's assign user 1 to the best channel quality, user 2 to the middle and user 3 to the worst. Then we increase the system capacity by adding more users whose channel qualities are better than user 1 3. We can see that user 1, user 2 and user 3 get 63kbps bandwidth when the total number of users is less than 10. This is because that the system is under loaded and there is enough bandwidth to meet the need of all the users. After that, bandwidth of user 3 decreases rapidly because the scheduler now attempts to allocate band-width to users with better channel qualities in order to gain high channel efficiency. When the number of users reaches 14, the minimum rate of user 3 is guaranteed by MRCA and user 3 can get a stable service rate of 10kbps. User 1 and user 2 do the same as user 3 except that user 2's gained bandwidth reduces to 10 kbps when the number of users reaches to around 20 and user 1 is about 24.

VI. Conclusion

In this paper, we investigate the problem of scheduling users with time-varying channels in wireless networks. A new generic Wireless Packet Scheduling Framework (WPSF) is proposed and its mechanism is analyzed. WPSF takes into account not only the quality of service (QoS) requirements but also wireless resource constraints of users. WPSF is applicable to any resource constrained wireless networks although we use the channel efficiency as a case study. We also present a Minimum Rate and Channel Aware (MRCA) scheduling algorithm which uses the above previous framework. Sim-ulation results show that, compared with other commonly pro-posed algorithms, MRCA can improve channel efficiency, while meeting users' minimum service rate requirements.

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